Environ. Sci. Technol. **2002**, *36,* 5315−5320

Hypoxia in the Baltic Sea and Basin-Scale Changes in Phosphorus Biogeochemistry

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Deep-water oxygen concentrations in the Baltic Sea are influenced by eutrophication, but also by saltwater inflows from the North Sea. In the last two decades, only two major inflows have been recorded and the lack of major inflows is believed to have resulted in a long-term stagnation of the deepest bottom water. Analyzing data from 1970 to 2000 at the basin scale, we show that the estimated volume of water with oxygen, <2 mL L^{-1}, was actually at a minimum at the end of the longest so-called stagnation period on record. We also show that annual changes in dissolved inorganic phosphate water pools were positively correlated to the area of bottom covered by hypoxic water, but not to changes in total phosphorus load, thus addressing the legacy of eutrophication on a basinwide scale. The variations in phosphorus pools that have occurred during the past decades do not reflect any human action to reduce inputs. The long residence time and internally controlled variation of the large P pool in the Baltic Sea has important implications for management of both N and P inputs into this eutrophicated enclosed basin.

Introduction

The depletion of dissolved oxygen in bottom waters is one of the common responses of aquatic ecosystems to eutrophication, and the semi-enclosed, brackish Baltic Sea has served as one of the classic examples of continuously growing problems of hypoxia and anoxia with cultural eutrophication (*1*). Bottom water oxygen deficiency influences not only the habitat of living resources (*2, 3*) but also the biogeochemical processes that control nutrient (*4, 5*) and trace metal concentrations (*6*) in the water column. Internal feedbacks on biogeochemical processes occur with oxygen depletion. These include increased P fluxes from sediments into overlying waters (*4, 7*) and reductions in the ability of these systems to lose nitrogen through denitrification (*8*), accelerating the rate of eutrophication.

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Bottom water oxygen concentrations in the Baltic Sea are also strongly influenced by physical factors, especially the inflow of saltwater (*9, 10*). Saltier, denser water from the North Atlantic flows into the Baltic Sea over a series of shallow sills in the Danish Straits and can displace stagnant, oxygen-depleted bottom water. Saltwater inflows are governed by large-scale and local meteorological variations and by sea level and salinity distributions (*11*). Only larger volume inflows of high-salinity water (≥17 PSU) have been defined as "major Baltic inflows" (*12*), with a total of 96 major inflows identified between 1897 and 1997, excluding the two World Wars (*11*) (Figure 1C). Few such major inflows have occurred since the mid-1970s, and in the last two decades, only two major inflows are recorded, in 1983 and 1993 (*13*). The lack of major inflows is believed to have resulted in a long-term stagnation of the deepest bottom water (*11*) with extensive areas of hypoxia and anoxia present in the deepest parts of the Gotland Deep (Figure 1A). Many authors have remarked on the biological and chemical effects of this stagnation on the Baltic Sea (*14*).

In this report, we use an extensive amount of data collected during monitoring cruises and research projects in the Baltic Sea and we compute a time series of basin-scale integrated total amounts of oxygen and nutrients. This approach takes into account concentrations that vary horizontally and vertically, i.e., specific water masses occupying different water volumes. Volume-weighted and integrated total amounts are then used to study the effect of basin-scale variations in oxic and anoxic conditions on phosphorus concentrations, a redox-sensitive nutrient (*4*). We report here basin-scale annual changes in hypoxic volumes with time that challenge the accepted view of a stagnant Baltic Sea and address the significance of oxygen on P biogeochemical cycles.

Methods

The hydrographic and chemical conditions in the Baltic Sea have been followed with oceanographic surveys since the end of 19th century. A wealth of these measurements have been compiled in the Baltic Environment Database (BED) at Stockholm University, and special data analysis tools have been developed (*15, 16*) (http://data.ecology.su.se/Models). Volumes of water and areas of bottom confined by oxygen isosurfaces of 2 mL L^{-1} as well as integrated amounts and average concentrations of total phosphorus (TP), dissolved inorganic phosphorus (DIP), and oxygen were computed with the Data Assimilation System (DAS, ref *15*) on 3D fields interpolated from observations in the entire basin of the Baltic Proper, including the Gulf of Finland and the Gulf of Riga (Figure 2).

A threshold concentration of 2 mL L^{-1} was chosen because benthic dwelling organisms are strongly affected by oxygen concentrations of <2 mL L^{-1} (*2*). In addition, "bottom" water samples of oxygen are routinely taken from several meters above the bottom and are not representative of concentrations at the sediment−water interface. Calculation of oxygen concentrations at the bottom below the diffusive boundary layer suggests that it is likely oxygen concentrations at the sediment−water interface are anoxic when bottom water oxygen concentrations are <2 mL L^{-1} (*17*).

The interpolation routine (*15*) starts with averaging all observations found within a horizontal 5 nautical mile square grid cell and with a vertical resolution corresponding to the depth distribution of measurements. Next, the grid cells with no measurements are filled by linear interpolation. Since the result of 3D interpolation depends on the order of elementary one-dimensional interpolations along each of three axes, an average of six possible permutations was used.

10.1021/es025763w CCC: $22.00
Published on Web 11/13/2002

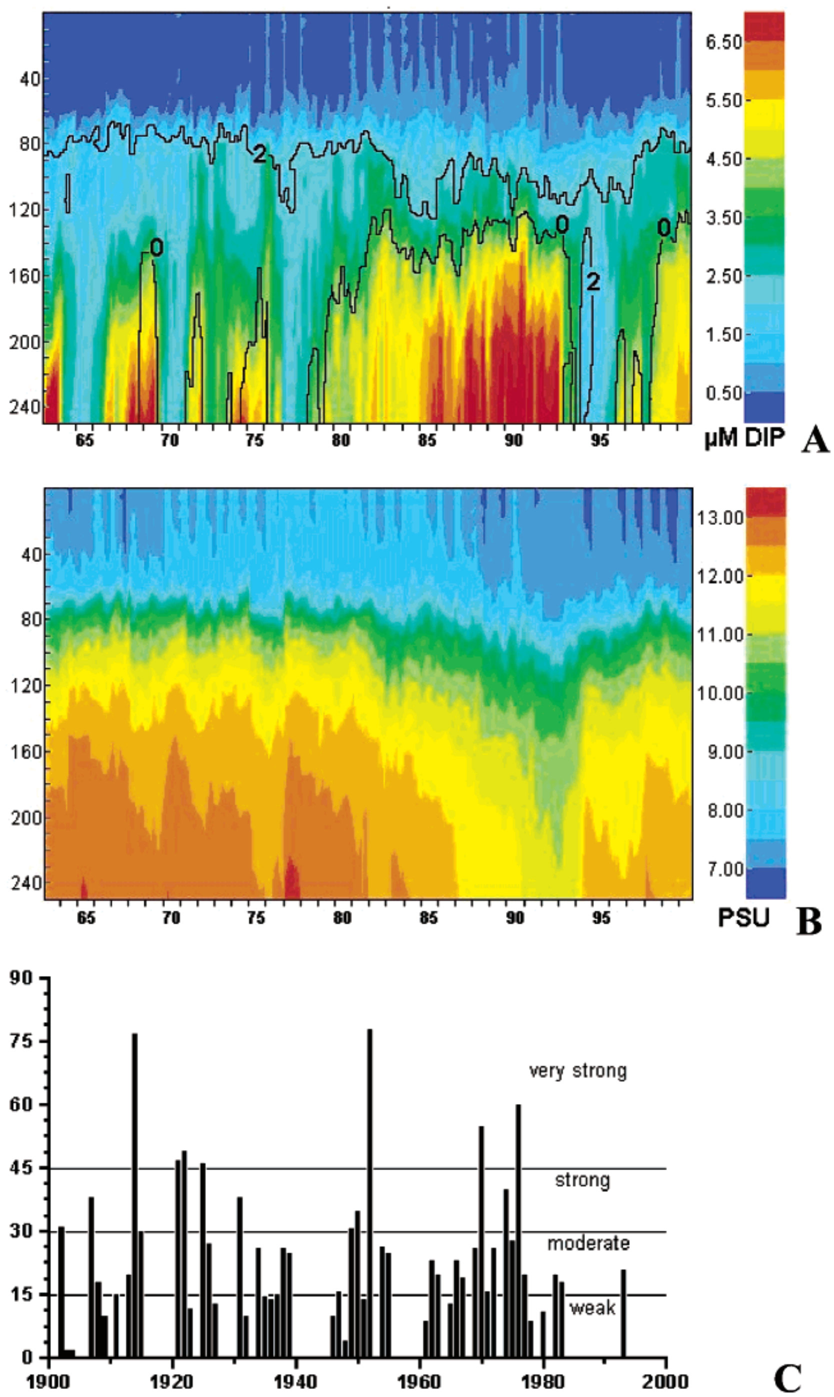


FIGURE 1. Classic view of the Baltic Sea as exemplified by conditions in the Gotland Deep. Time−depth contour plots of oceanographic parameters were constructed with the SwingStations tool (*16*) from measured vertical profiles averaged over 57°17′−57°22′ N, 19°55−20°06′ E area within every successive 90 days during 1963−2000. Depth in meters. (A) Time−depth contour plot of dissolved inorganic phosphate (μM DIP, 1245 vertical profiles) and isopleths of O_2 (1552 vertical profiles) for 1963−2000. The isopleths represent 2 and 0 mL L^{-1}. Negative oxygen concentrations were determined as hydrogen sulfide equivalents, where 1 mL L^{-1} $H_2S = -2$ mL L^{-1} O_2 (*9*). (B) Time−depth contour plot of salinity (PSU, 1620 vertical profiles) variation for 1963−2000. C. Inflow index at the entrance to the Baltic Sea (redrawn from Schinke and Matthäus (*11*)).

To prevent unrealistic extrapolations, these were extended for only a few dozen miles, whereas concentration is kept constant further onward. Finally, the field is smoothed by a Tukey's cosine filter. Each field constructed with DAS over a specific time interval represents one unique quantity, which prevents uncertainty estimates. Although every field is based on several hundred (TP) to several thousand (oxygen, DIP) observations, the spatial coverage in some years was less uniform than in others (Figure 2). Preliminary analysis of the fields allowed us to exclude questionable data, typically either significantly higher or lower than those measured nearby by other research vessels or with poor vertical resolution. Total phosphorus was less extensively measured before the mid-1970s, and DIP pools are considered more reliable than TP pools. Therefore, the analysis has been based upon DIP even though phosphorus loading is expressed as TP.

Data on nutrient loading have been derived from several published sources. The Helsinki Commission (HELCOM) has compiled data on urban and industrial nutrient loads to the Baltic since 1979 (*13, 18, 19*). River loads and other coastal

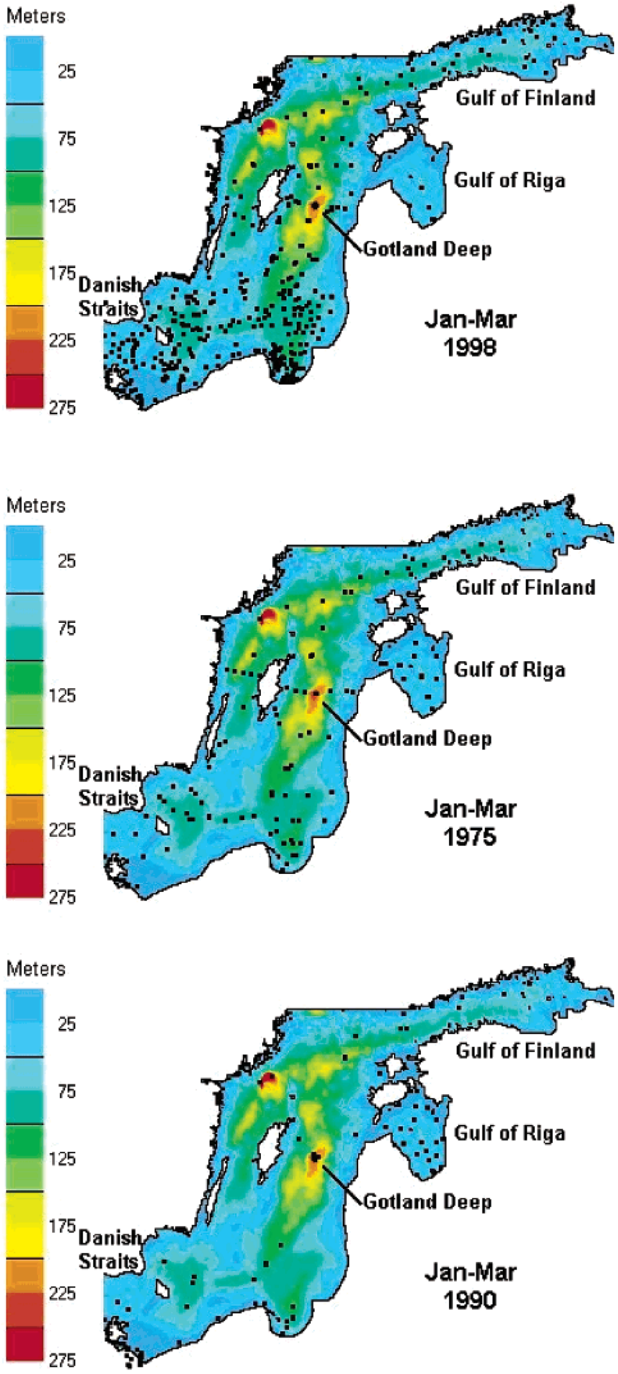


FIGURE 2. Depth distribution in the Baltic Proper with examples of good (top), typical (middle), and poor (bottom) data coverage. A single dot at the routinely monitored stations often represents several vertical profiles taken by different research vessels during the period January−March.

diffuse inputs (1970−1990) have been taken from Stålnacke et al. (*20*), providing a monthly data set on nutrient loads, based on 110 sampling stations within the Baltic Sea catchment. For the period 1991−1998, this data set has been updated with a methodology similar to ref *20* using nutrient discharge data obtained from various environmental agencies.

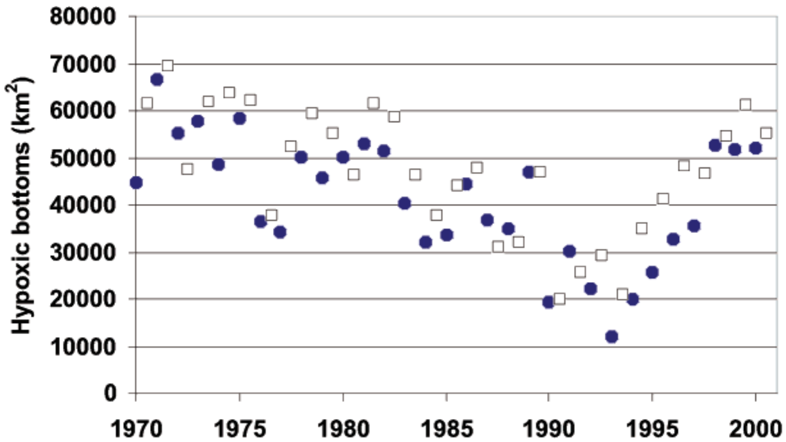
Results and Discussion

Oxygen in Bottom Waters. Areas of winter and summer hypoxic bottoms were calculated for the period 1970−2000 (Figure 3). Areas of bottom underlying water with oxygen concentration less than 2 mL L^{-1} varied from less than 12 000 km^2 up to 70 000 km^2, or occupying 5%−27% of the total bottom area. Contrary to expectations, the area of bottom with the least hypoxic overlying water occurred during the largest so-called stagnation period from 1983 to the next major inflow in 1993 (Figure 1). Careful inspection shows that during this period intermediate depths of 80−120 m in the water column had higher oxygen concentrations than during other years (Figure 1A). In the absence of major Baltic inflows, the reduced salt influx cannot support vertical salinity gradients against turbulent diffusion allowing for oxygen to penetrate to deeper depths in addition to the lateral advection of oxygen (*10, 21*). The lack of major inflows further enhances the weakening of stratification, resulting in an erosion and deepening of the halocline facilitating many intermediate inflows (*22*), i.e., the inflow of saline water of <17 PSU, which do not penetrate into the deepest areas of the Baltic Sea and are not included in the inflow index. After 1993, several smaller inflows have occurred almost every year (*22*); however, they failed to fulfill the criteria defined by the intensity index used (*12, 13*). These numerous intermediate inflows oxygenated vast areas of the Baltic Sea during the so-called stagnation period.

Our perception of conditions in the Baltic is biased by the habit of studying individual deep stations such as the Gotland Deep (Figures 1 and 2). Actually, the hypsographic curve, i.e., the distribution of bottom area with depth, shows that only 10% of the bottom area is situated deeper than 108 m. Although conditions at the deepest point have been of interest of their own, they are far from representative of the entire Baltic system. The data presented in Figure 3 clearly show that the estimated volume of water with oxygen <2 mL L^{-1} was actually at a minimum at the end of the longest so-called stagnation period on record, and therefore, the perception that the Baltic Sea was a stagnant basin and the resulting increase in anoxic areas for the period of 1976−1993 are not supported by the data. Reduced saltwater inflows into this brackish ecosystem does not automatically lead to hypoxia in deeper waters. Vertical density gradients, which are established in enclosed seas such as the Baltic mainly by salt, are weakened by the lack of saltwater inflows as hypothesized by Gerlach (*10*). However, our analysis clearly demonstrates the magnitude of this effect and allows us to investigate empirical relationships among hypoxic area, volume, and phosphorus biogeochemistry.

Phosphorus Biogeochemistry. It is well known that sediments can act as “sinks” for P under oxic conditions primarily due to phosphate interaction with Fe, and sediments can act as “sources” during hypoxic situations (*4, 7*). Given that oxygen conditions are strongly related to inflow events, phosphorus dynamics should also be related to this naturally occurring phenomenon. Therefore, we have explored the relationship between phosphorus pools and oxygen conditions.

At the basin scale, changes in the integrated water column DIP pool from one winter to another are coherent with changes in the area of hypoxic bottoms (Figure 4A) with extreme variations of up to 112 × 10^3 ton of DIP and changes in hypoxic area of 28 000 km^2, annually. If we compare the variation in water column DIP pools to changes in the TP loads to the Baltic Proper, we see that TP loads cannot account for such large changes between years in the DIP pool. TP loads varied from 23 × 10^3 to 37 × 10^3 ton yr^{-1} in the period 1970−1998, without significant long-term trends (Table 1). While there have been some local reductions in TP load (*13*), the drastic reduction in fertilizer consumption and increases in sewage treatment capacity after the political changes in 1989 have not substantially decreased the TP loading (*23*), as has been claimed (*24*). Neither the variations observed in TP loads ($(30 \pm 3) \times 10^3$ ton yr^{-1}) nor the possible reductions



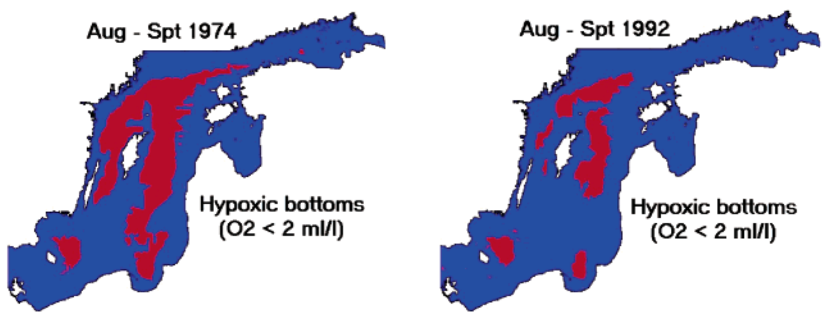


FIGURE 3. Long-term variations of the bottom area covered with waters containing less than 2 mL L^{-1} oxygen. Oxygen fields were averaged over August−September (open squares) and January−March (closed circles) for each calendar year for the Baltic Proper, which includes the Gulf of Finland and the Gulf of Riga. Spatial distributions for August−September in 1974 and 1992 are shown at bottom.

in these loads, which can be estimated at less than 1×10^3 ton yr^{-1} for the Baltic Proper from 1990 to 1995 (*18, 19*), can explain the natural annual variations in P stocks in the water column, which are 1−2 orders of magnitude larger than the variations observed in external P inputs (Table 1). Mass-balance calculations of the transport of nutrients between basins suggest that on average the Baltic Proper exports some 17×10^3 ton yr^{-1} TP to the adjacent basins, including 11×10^3 ton yr^{-1} TP exported out of the Baltic Sea through the Danish Straits (*25*). These estimates clearly demonstrate that the annual change in TP cannot possibly be due to advection between basins.

A significant negative relationship was found between mean oxygen and DIP concentrations within the hypoxic volume, indicating an anoxic release of phosphorus (Figure 4B). The weaker correlation between basin-scale changes in hypoxic areas and P stocks is only expected, since interannual variations in the DIP pool integrated over the whole Baltic Proper are affected by many other processes as well. The size of DIP pools averaged over January−March varies according to interannual and regional variations of the commencement and duration of spring and fall phytoplankton blooms, affecting DIP concentrations in a large volume of the surface layer. Given the same rate of winter buildup of DIP stocks, late autumn and early spring blooms would reduce average winter concentrations, while early autumn and late spring blooms would result in higher concentrations. Furthermore, our basin-scale approach neglects regional variations in the history of hypoxic conditions, influencing both the duration and degree of accumulation or depletion of P stocks in sediments. Finally, DIP release and precipitation sites do not necessarily concur; thus, they do not obey the same biogeochemical stoichiometry. Nevertheless, a relationship between redox alterations and DIP variations has clearly emerged.

The DIP accumulation in bottom water due to the expansion of the hypoxic area is about the same as the magnitude of DIP losses during shrinkage of the hypoxic area (Figure 4A), indicating that at a basinwide scale the P bottom water exchange is reversible in the Baltic. We can estimate rates of sediment release that must occur to account for increases in the P pool. If an average rate of 2 tons km^{-2} is released over a year in the expansion phase (derived from the slope of the relationship in Figure 4A), a sediment−water release of 0.18 mmol P m^{-2} d^{-1} is obtained, or in an extreme case, if 100×10^3 ton of P is released from an area of 20 000 km^2 (derived from the ranges observed in Figure 4A), a sediment−water release of 0.44 mmol P m^{-2} d^{-1} is obtained. These estimated rates are not uncommon for hypoxic situations either in the Baltic (0.7 mmol P m^{-2} d^{-1} in occasional anoxic events (*26*), up to 0.65 mmol P m^{-2} d^{-1} during transitions from oxic to anoxic periods (*27*)) or in U.S. estuaries with a range of 0.3−3.0 mmol P m^{-2} d^{-1} (*28*). Using a limited number of sediment cores from the Gotland Basin, annual sediment release since the early 1970s has been estimated to be 14×10^3 ton of P (*29*). This estimate accounts for only a portion of the bottom that is frequently anoxic and cannot be extrapolated over the entire Baltic, which has a much larger area that periodically is anoxic. These different calculations demonstrate that an exchangeable pool of P is present in the sediments, which can account for the yearly changes in water column P pool sizes.

Importance to Management. Phosphorus is an important nutrient in eutrophication and can be an important nutrient limiting production in estuaries (*30*). It is relatively easy to manage for P in sewage treatment plants, which has led to large reductions in TP loading in many European rivers during the past decade (*31*). Large reversible variations in sediment P storage, which are related more to climate than to anthropogenic loading, will make it difficult on the short

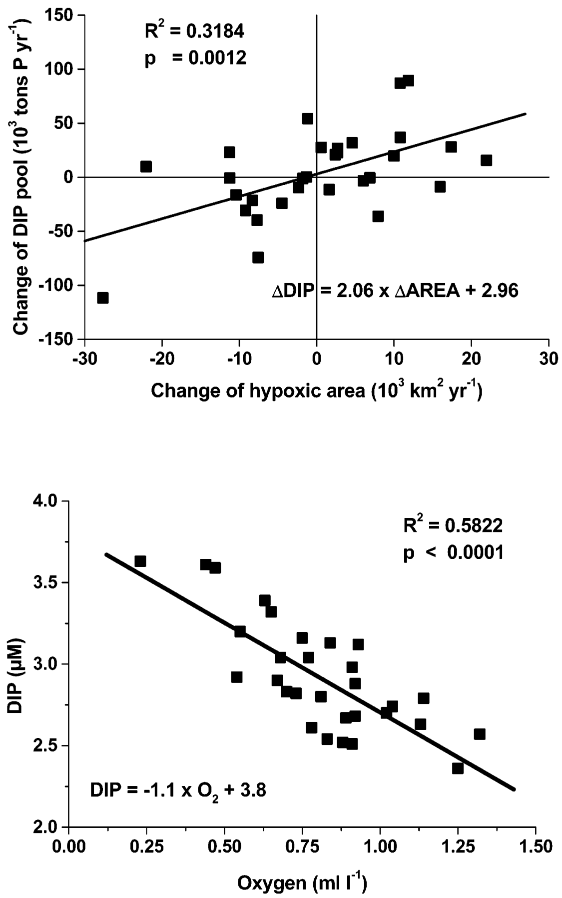


FIGURE 4. Relationships between dissolved inorganic phosphate (DIP) and oxygen conditions in the Baltic Sea. (A) The change in water pools of DIP from one winter (January−March) to the next, plotted against the contemporaneous change in the area of hypoxic bottom underlying waters of <2 mL L^{-1} oxygen. (B) Mean DIP and oxygen concentrations averaged over hypoxic volumes with water containing less than 2 mL L^{-1} oxygen within August−September fields in 1970−2000.

term to manage for P as the limiting nutrient in the Baltic. However, possible reductions in the TP load over the long term, i.e., several decades, to those levels observed 100 years ago prior to large-scale perturbations of nutrient biogeochemical cycles ($\sim$10 $\times$ 10^3 ton yr^{-1}) (*32*) could have a substantial impact upon eutrophication in the Baltic with time. A drastic reduction in the N load, while the P concentrations remain high, might be ineffective since it will enhance nitrogen fixation by cyanobacteria (*33*). However, on the long term, managing only for P and not for N is also short-sighted. P limitation would lead to a lower utilization rate of N in the Baltic and result in a greater export of N in the outflowing waters to the N-limited Kattegat (*34*), aggravating eutrophication problems in the heavily impacted transitional waters of Denmark (*35*).

Using basin-scale integrated approaches, we show that annual changes in DIP water pools were positively correlated to the area of bottom covered by hypoxic water, but not to changes in TP load, thus addressing the legacy of eutrophication with important implications for management of nutrient inputs into the Baltic Sea (*13, 25*). We have demonstrated here that climatically driven variations in saltwater inflows and, thus, bottom water oxygen concentrations have a profound influence on P biogeochemical cycles and basinwide concentrations of P. These results emphasize the need to unravel the relative importance of the human impact and to distinguish those impacts from climatic effects.

TABLE 1. Time Series of Annual Total Phosphorus (TP) Load, Total Amount of Dissolved Inorganic Phosphorus (DIP) in the Water, and Area of Sediments Exposed to Hypoxia in the Baltic, Which Includes the Baltic Proper, the Gulf of Finland, and the Gulf of Riga, Averaged for January−March[a]

year	TP load (10^3 ton yr^{-1})	DIP (10^3 ton)	hypoxic area (10^3 km^2)
1970	30	322	45
1971	27	337	67
1972	25	337	55
1973	23	358	58
1974	31	387	49
1975	28	407	59
1976	25	416	36
1977	31	407	34
1978	29	398	50
1979	29	374	46
1980	35	406	50
1981	34	432	53
1982	30	433	52
1983	27	456	40
1984	28	434	32
1985	33	423	34
1986	33	460	44
1987	33	386	37
1988	37	385	35
1989	32	474	47
1990	30	362	19
1991	28	449	30
1992	26	410	22
1993	28	393	12
1994	29	357	20
1995	28	354	26
1996	23	353	33
1997	26	376	35
1998	30	404	53
1999		458	52
2000		486	52

[a] TP load complied from refs*13* and *18−20* and other sources as indicated in the text.

This approach can also be implemented in other impacted marine areas where a wealth of monitoring data exists.

Acknowledgments

This work was supported in part by Marine Research on Eutrophication Program (MARE). We gratefully acknowledge and thank all institutions and individuals who have contributed data to the Baltic Environmental Database. A. Sokolov is thanked for further development of DAS tools. Valuable comments have been provided by B. von Bodungen, R. Elmgren, B. Gustafsson, and three anonymous reviewers.

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Received for review May 3, 2002. Revised manuscript received October 9, 2002. Accepted October 16, 2002.

ES025763W